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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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# **An Analytical Performance Assessment of a Fuel Cell-Powered, Small Electric Airplane**

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Rapidly emerging fuel cell power technologies may be used to launch a new revolution of electric propulsion systems for light aircraft. Future small electric airplanes using fuel cell technologies hold the promise of high reliability, low maintenance, low noise, and—with the exception of water vapor—zero emissions. This paper describes an analytical feasibility and performance assessment conducted by NASA's Glenn Research Center of a fuel cell-powered, propeller-driven, small electric airplane based on a model of the MCR-01 two-place kitplane.

## **Introduction**

An analytical performance model of a Proton Exchange Membrane (PEM) fuel cell propulsion system is developed and applied to a notional, two-place light airplane modeled after the Dyn'Aéro MCR-01 ULM kitplane. This analytical assessment is conducted in parallel with an ongoing effort by the Advanced Technology Products Corporation and the Foundation for Advancing Science and Technology Education. Their project—partially funded by a NASA grant—is to design, build, and fly the first manned, continuously-propelled, non-gliding electric airplane.

In this study, a PEM fuel cell stack is fed pure hydrogen fuel and humidified ambient air via a small automotive centrifugal supercharger. The fuel cell performance models are based on chemical reaction analyses calibrated with published data from the fledgling U.S. automotive fuel cell industry. Electric propeller motors, rated at two shaft power levels in separate assessments, are used to directly drive a two-bladed, variable-pitch propeller without the need of a reduction gearbox. Fuel sources considered are compressed hydrogen gas and cryogenic liquid hydrogen. Both of these fuel sources provide pure, contaminant-free hydrogen for the PEM cells.

Also assessed is a hybrid fuel cell/battery propulsion system, where a smaller fuel cell provides power for the minimum base demand at the cruise condition and for battery charging. In this design, the battery supplies additional boost power for the takeoff, climbout, and missed approach mission segments. An analytic model of the conventional, reciprocating engine-powered MCR-01, validated using published performance data, is used to compare with the electric airplanes.

In addition to the off-the-shelf (current) technology level investigated, weight and volume estimates of intermediate and advanced technology levels are also evaluated. These notional, futuristic technology levels require enabling advances in miniaturization, structures, materials, supercooled electronics, and power and heat management systems. The detailed power management system and fuel cell design, system integration, cost, airworthiness, and certification issues are complex and are beyond the scope of this conceptual study.

## **Method of Analysis**

The fuel cell power and propulsion systems are analytically modeled using the Numerical Propulsion System Simulator (NPSS) computer code (Ref. 1). NPSS is an object-oriented engine cycle simulation program jointly developed by NASA and members of the U.S. aeropropulsion industry. It offers the ca-

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pability of executing disparate external component performance prediction models and controlling their execution with its solution algorithm. NPSS is used in this study to analytically connect the various fuel cell propulsion system components, to perform a balanced, one-dimensional aerothermodynamic cycle simulation, to compute propeller thrust levels, and to calculate the air and hydrogen flow rates needed to deliver required electric power and propeller thrust levels. Further information regarding the performance modeling of the fuel cell system may be found in Reference 2.

A component diagram of the fuel cell propulsion system is shown in Figure 1. The solid shapes represent components that are analyzed using NPSS. Air at user-specified ambient conditions flows into an automotive centrifugal compressor driven by a small electric motor. This supercharger, modeled using the manufacturer's performance specifications (Ref. 3), is required in most aircraft fuel cell propulsion systems, particularly at higher altitudes, to ensure adequate airflow rates through the cell stack. The compressed air flows through a humidifier and into the cathode portions of the stack. Although the humidifier's weight is accounted for, the humidification process is not thermodynamically modeled, nor is the humidifier rigorously sized. This will be corrected in future studies. Unlike a reciprocating engine system, a fuel cell system is more modular and its components may be distributed within reason throughout an aircraft as required by packaging constraints.

Pure hydrogen fuel enters the anode portions of the stack and is delivered by the fuel system described below. The fuel cell's weight and volume are modeled by scaling data released by the General Motors Global Alternative Propulsion Center in 2001 for their newest automotive stack (Ref. 4). This stack represents the best-built stack to date reported in the open literature in terms of volumetric efficiency. Power density is reported at 0.74 hp/lb (1.24 kW/kg) at its maximum continuous rated power level. A heat exchanger is used to reject waste heat from the cell. Like the humidifier, the heat exchanger is not thermodynamically modeled or sized within NPSS; however, its estimated weight is considered.

The batteries chosen for the hybrid system are of the lithium-ion variety and are selected for their relatively high energy density and technological maturity. In the hybrid systems, the fuel cell system is smaller, lighter, and provides only enough power to satisfy base power demand duties for part-throttle cruising flight and battery recharging. The battery power augments the fuel cell power on takeoff, portions of the climb segment, missed approaches, and emergency situations. They also serve as a redundant power supply in the event of a fuel cell system failure. The batteries are assumed to provide an energy density of 148 W-hr/kg and are allowed to discharge to a 30% state of charge before recharging. Battery degradation caused by discharging to low charge states may be acceptable in lower-cycle aviation applications.

The power generated by the cell and battery systems, where applicable, is conditioned by electrical power management and distribution (PMAD) components that are sized using available data and past experience. The conditioned electrical power is used for the electric propeller motor, supercharger motor, and auxiliary power requirements for the fuel cell and other onboard aircraft flight systems.

The electric propeller drive motor is modeled using scaled performance data based on a UQM Technologies Model SR286 motor (Ref. 5). The SR286 is a compact, lightweight, efficient, brushless permanent magnet motor intended for use in electric, hybrid electric, and fuel cell-powered vehicles. It incorporates its own drive electronics and microprocessor-controlled current inverter. Speed reduction gearboxes are unnecessary. The unscaled (100 kW) motor performance is illustrated in Figure 2. The efficiency ratings shown are mapped into NPSS and applied to the performance calculations. The maximum takeoff rated power—used for takeoff, some of the climb segment, missed approach, and emergency situations—is limited to five minutes of intermittent use due to heat rejection constraints. Power output is limited to maximum continuous levels or less for the remainder of the mission. The motor uses an internal glycol-based liquid cooling system. In a propeller-driven aircraft application, it may be possible to increase the motor's maximum continuous power levels (or the time at maximum takeoff rated power) relative to stationary or even automotive applications due to the enhanced, constant cooling flow provided by the propeller.

In this study, the UQM motor is scaled in power, dimensions, and weight to two sizes. The larger motor size is selected to duplicate the sea level power output of the MCR-01 original equipment manufac-

turer's 81 bhp Rotax 912A piston engine. This size—60 kW (81 bhp) intermittent and 30 kW (40 bhp) continuous—is sufficient to achieve takeoff, climb, and cruise performance comparable to the original MCR-01. A smaller motor, selected to provide just enough continuous power to maintain an airspeed of 75 knots at 3000 feet, is rated at 37 kW (49 bhp) intermittent and 12 kW (16 bhp) continuous. This smaller motor size is intended to be used only for proof-of-concept or demonstration flights of electric aircraft. Indeed, the smaller motor's power is only marginally sufficient to maintain a cruise speed on the proper side of the airplane's thrust-power curve, as shown in Figure 3. The power curves in this figure are calculated using the MCR-01's maximum gross weight, aerodynamics, and a service ceiling potential climb rate of 100 ft/min using standard atmospheric properties.

Thrust calculations are made throughout the operating envelope using the shaft power and speed results from NPSS and the propeller performance prediction method described in References 6 and 7. The propeller selected is a typical variable-pitch, two-bladed propeller appropriate for use in general aviation light aircraft. Installed efficiency curves for a fixed propeller speed of 2550 RPM are illustrated in Figure 4. Unlike reciprocating engines, a feature of electric motors is their ability to generate their rated power throughout a relatively wide range of shaft speeds (See, e.g., Figure 2). This feature allows the motor shaft speed and blade angle to be optimized to provide maximum propeller thrust for given flight conditions and available power. Similarly, for a given thrust requirement, the shaft speed may be optimized for minimum hydrogen fuel use. In this study, NPSS performs this optimization task analytically, resulting in up to five percent higher propeller thrust in some regimes. In reality it is envisioned that a full-authority digital electronic control system would be developed to exploit this benefit of electric aircraft.

In order to avoid membrane poisoning, PEM fuel cells require high-purity hydrogen fuel, which is difficult to obtain from other hydrogen fuel sources via current chemical reforming techniques. Reforming and purification systems also contribute additional weight and volume penalties that are not easily tolerated in aircraft. It is also more difficult to match fuel supply and demand rates with these added systems. For these reasons, only pure compressed gaseous hydrogen and cryogenic liquid hydrogen fuel sources are considered in this assessment. Advanced compressed gas tanks made of lightweight composite materials are now becoming available. These tanks, with certification to 5000 psi anticipated, are used in this study as containers for high-pressure hydrogen. Cryogenic liquid hydrogen tanks are also used in this study. They are insulated, kept at near-atmospheric pressure, and offer the advantage of some conformal shaping to available aircraft interior volume. For long-term storage and fire safety, the tank relief venting presumably would be routed through a catalytic combustor or perhaps even the fuel cell stack. Unlike current practices involving petroleum-based aviation fuels, hydrogen in either form is difficult to store in the available wing volume. Instead, a volume of six cubic feet is allotted in the kitplane's rear fuselage area for compressed gas or liquid hydrogen fuel. As powerplant component miniaturization takes place in the anticipated intermediate and advanced technology level scenarios (described below), an additional 2 and 4 ft<sup>3</sup> of tank volume is assumed to become available, respectively. The use of compressed hydrogen is ruled out for the advanced technology level since a cryogenic heat sink is necessary for the assumed supercooled avionics and electric motor. Tank sizing models using hydrogen's thermodynamic properties are developed and used to determine available fuel quantities.

NASA's Flight Optimization System computer code (Ref. 8) is used to compute aircraft mission performance. This code is a multidisciplinary system of analysis modules used throughout the aeronautics community for aircraft synthesis, sizing, performance assessments, and optimization. In this study, an analytical model of the MCR-01 is developed using specifications gathered from the aircraft and engine manufacturers and other published sources (Refs. 9, 10, and 11).

The airplane's maximum lift-to-drag ratio is 16.3. This figure is quite good; however, like most light aircraft with strict stall speed requirements (Ref. 12), it is difficult to cruise at that level of performance due to aerodynamically oversized wings. An advantage of small electric airplanes, to be described below, will be their ability to cruise more efficiently at higher altitudes nearer their maximum lift-to-drag ratio.

The empty weights of the electric airplanes are calculated using the MCR-01 component and equipment weights (less the weight of the Rotax 912A propulsion system) and adding them to the calculated weights of the electric propulsion and hydrogen fuel systems. Aircraft balance and stability and control

issues are not considered. As stated above, weight estimates of hypothetical intermediate and advanced technology levels are also evaluated. The technology vision for each propulsion subsystem is summarized in Table 1. Specific weight estimates used in this study (in units of hp/lb at intermittent power) are shown in the table for the fuel cell stack, fuel cell system, electric drive motors, and power electronics. The component weights assumed for the intermediate and advanced technology levels are little more than educated guesses, but when analyzed together as a system, they provide insight as to the ultimate practicality of small electric airplanes.

The mission consists of typical warm-up, taxi-out, and takeoff segments, followed by an optimized climb at the best throttle setting for minimum fuel use to the cruise altitude. Cruising speed and altitude are optimized for cases using the larger propeller motor, but airspeeds less than 130 kts are not permitted. Demonstration, proof-of-concept aircraft using the smaller motor cruise at 75 kts at 3000 ft. Typical descent, approach, landing, and taxi-in segments follow the cruise segment. No reserve mission is considered. The airplane is flown at fixed gross weights without sizing and still-air range is calculated. The manufacturer's maximum takeoff gross weight (992 lb) is never exceeded. Data for payload-range diagrams are computed.

## Results and Discussion

An aircraft excess specific power ( $P_S$ ) assessment is used to compare the performance levels of all propulsion systems. The MCR-01's  $P_S$  performance with its original equipment Rotax 912A is shown in Figure 5.  $P_S$  contours are calculated in increments of 5 ft/s. Additional contours of constant energy height are shown as dotted lines in increments of 1000 ft. The 912A-equipped airplane's takeoff and continuous  $P_S$  curves are nearly identical due to the comparable power levels—81 bhp for five minutes at 5800 crank RPM and 79 bhp at 5500 RPM, respectively. The 912A is naturally aspirated and  $P_S$  therefore diminishes with altitude. Calculations are limited to below the approximate limit of operation without the use of supplemental oxygen (Ref. 13). Maximum takeoff gross weight, standard atmospheric properties, and a sustained load factor of unity is assumed everywhere for steady, level flight.

The first fuel cell powerplant, even though it is designed to deliver sea level takeoff-rated shaft power identical to the original equipment, behaves quite differently. Since the fuel cell stack necessarily uses a small compressor for intake manifold pressurization and efficient electrochemistry, the electric propulsion system can deliver virtually constant shaft power at any altitude in its operating envelope. The electric airplane's propeller thrust at altitude therefore can be much higher than a conventional, naturally-aspirated reciprocating engine of comparable sea level power and equivalent propeller. And due to the propeller speed optimization of the electric system and added mechanical losses of the reciprocating system, the electric airplane experiences slightly better sea level performance at runway speeds as well. The takeoff-rated  $P_S$  performance of this system is shown on the left in Figure 6. Although reciprocating engines certainly can be, and frequently are, turbocharged, adding a small compressor to a fuel cell system is especially attractive due to the very low airflow rates involved.

Unlike the reciprocating airplane, the electric airplane's performance is significantly worse at continuous power levels, as seen on the right in Figure 6. Its long-duration power output is substantially limited by heat rejection constraints. Its cruise speed is limited to about 130 kts at this power and only then at high altitudes. Although continuous  $P_S$  levels at higher altitudes are comparable to the 912A-powered airplane, the electric airplane still "prefers" to cruise at higher altitudes where the combination of specific fuel consumption, lift-drag ratios, and specific range levels are more optimal.

Due to these traits, perhaps a better application of supercharged fuel cell powerplants would be for high-altitude general aviation aircraft with pressurized cabins. The supercharger could be used to supply cabin air as well as cathode pressurization. A general aviation electric airplane flying at 20,000 ft or more would have a cruise-sized wing, avoid low-altitude turbulence, and could fly over many storm systems.

The smaller electric powerplant's  $P_S$  performance is shown in Figure 7. As discussed earlier, this is a proof-of-concept system designed to deliver only enough continuous power to maintain 75 kts at 3000 ft.



Aircraft weight statements are calculated by subtracting propulsion and fuel system weights from the 912A-equipped MCR-01 (Figure 8) and adding fuel cell and compressed hydrogen system weights (Figure 9). The weight breakdown shown in Figure 9 uses the fuel cell system with comparable 912A sea level power and compressed hydrogen fuel. The fuel cell powerplant accounts for over half of the 992 lb gross weight statement. If the manufacturer's takeoff gross weight is not to be exceeded, no optional payload may be added to this electric airplane. Indeed, assuming off-the-shelf technology levels, the pilot may weigh only 128 lbs—considerably less than the 170 lb standard used in Reference 12. And the 6 ft<sup>3</sup> of fuselage volume allows only 4.7 lbs of compressed hydrogen gas at 5000 psi to be stored. Limited fuel volume forces this electric airplane to fly its entire mission at nearly constant gross weight. But if the available fuselage volume is used to store cryogenic liquid rather than compressed hydrogen, then 20 lbs of fuel may be carried, and with considerably less tank weight. The classic volume problem associated with most hydrogen vehicles appears to apply here as well. An offsetting effect, however, is the fuel cell's miserly consumption of hydrogen: brake specific fuel consumption levels range from 0.10 lb/hr/bhp at sea level to only 0.11 lb/hr/bhp at 10000 ft. The higher figure is due to higher supercharger power demand at altitude.

The use of a payload-range diagram is one method to illustrate airplane performance as well as utility. These diagrams are used here to compare all airplane powerplants. The 81 bhp PEM systems are shown in Figure 10 along with the predictions for the Rotax 912A-equipped airplane. Rather than plot a "negative payload," as would be the case with the PEM systems, the weight of the pilot is added to the payload. The use of liquid hydrogen allows much more fuel to be carried for a substantial range increase; however, both systems carry very lightweight pilots. Advances in technology are required to make these systems viable.

The reduced-power, proof-of-concept electric powerplants fare better in a payload-range comparison, albeit with lower airspeeds and ceilings, longer field lengths, and inferior climb rates. The weight and size of many electrical systems do not scale linearly with power. The weight of the PMAD systems, for example, increase substantially with higher power requirements. This is evident even in the relatively small 81 bhp PEM system, where PMAD components account for a third of the overall powerplant weight. This unfavorable scaling effect may even make many larger electric aircraft applications impractical. Smaller electric systems, however, benefit from this scaling, as can be seen in Figure 11. The PEM-battery hybrid performs poorly compared to the simple PEM system in this assessment due to the lithium-ion battery's relatively high weight. It may be desirable in a demonstration airplane, however, to carry a redundant power supply.

When the component specific weights assumed for the intermediate and advanced technology levels (Table 1) are applied, the performance gap between cryogenic electric and reciprocating systems closes. These results are plotted in Figure 12. It is difficult to draw definitive conclusions from the educated guesses at weight reduction used in these projections, but it is encouraging to see emerging electric aircraft become competitive with mature reciprocating aircraft. Compressed gas systems carrying limited quantities of fuel still lag in range. The primary use of these small kitplanes, however, is often for sport recreation and not necessarily for long-distance travel. The simplicity and long-term storage benefits of compressed gas fuel systems may outweigh the range benefit of cryogenics.

A propeller driven by an electric motor has at least four performance benefits relative to one driven by a reciprocating engine. The first benefit, discussed above, is the high excess specific power levels that are possible with electric airplanes. Each of the other benefits is related to the ability of electric motors to provide their rated power levels over relatively wide ranges of shaft speeds. This versatility is difficult for an internal combustion engine to match. The second benefit, as discussed previously and implemented analytically in this study, is to optimize the speed and blade angle of a variable-pitch propeller to gain a small amount of additional thrust in some regimes. A third benefit, which also arises from this extra degree of operational freedom, can be extended to fixed-pitch propellers. Such a "variable advance ratio" propeller system could enhance the market for simpler, lower-cost, fixed propellers.

The fourth benefit is the potential for noise reduction. Electric propulsion offers the advantages of lower community and cabin noise. The most obvious acoustic advantage of electric flight will be the

absence of the noise, vibration, and harshness produced by conventional reciprocating engines. Even with efficient muffling systems, noise and vibration are difficult to suppress, and they remain leading sources of pilot fatigue. Reciprocating engines also contribute somewhat to the noise levels propagating to community observers on the ground. Although the propeller is typically the dominating noise source for the peak A-weighted noise levels measured for takeoff certification (Ref. 14), piston engine noise can make significant contributions to the rest of the flyover noise history. The second possibility for noise reduction is less obvious, and is again linked to the electric motor's speed versatility. Reciprocating engines typically produce their design rated power at or near their peak shaft speed. If a low-noise takeoff is attempted by reducing propeller speed, shaft power is also reduced. Such derated takeoffs are seldom tolerated in general aviation due to punishing performance effects, such as increased field lengths and poor climb rates. With electric motors, however, low noise, low shaft speed takeoffs using high power levels and blade angles are possible because much of the thrust lost with reduced propeller speed can be recovered. Preliminary calculations made by this office indicate that propeller noise reductions of up to 8 dBA are possible using derated shaft speed takeoffs with little performance loss. The same derated takeoff in a similar, but piston engine-driven, airplane would result in poor climb performance that likely would not be tolerated.

## Conclusions

Preliminary results indicate that flight may be possible using off-the-shelf fuel cell and power management technology levels, albeit at reduced speed, climb rate, range, and payload-carrying capability. Aircraft performance appears sufficient to fly a technology demonstration, proof-of-concept type vehicle using today's automotive-derived fuel cell and power systems. Only light aircraft, such as the MCR-01 considered here, are anticipated to be feasible with near-term technology due to their relatively low, automobile-like power requirements. Advanced fuel cell and power management technologies will be needed to achieve comparable reciprocating engine aircraft performance and utility and to enable the design of larger electric aircraft. Fuel cell and power management system weight and hydrogen fuel system volume are critical challenges. Heat management is critical to the practical operation of any fuel cell-powered application and requires more rigorous modeling. An efficient, safe airport hydrogen fueling infrastructure also must be in place if electric aircraft are to be economically viable. A global hydrogen economy also remains elusive. These issues aside, electric aircraft propulsion holds the promise of clean, reliable flight with several novel performance and noise reduction benefits.

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Table 1.—General assumptions used for technology level projections

	<b>Off-the-Shelf Technology</b>	<b>Intermediate Technology</b>	<b>Advanced Technology</b>
	<i>Based on commercially-available products</i>	<i>Based on current government and industry research and development</i>	<i>Based on government and university laboratory demonstrations</i>
<b>Fuel Cell Stack</b>	Automotive-derivative PEM fuel cell stack (~1.0 hp/lb)	Higher operating temperature PEM fuel cell stack; higher power densities (~2.0 hp/lb)	New type of fuel cell with different chemistry, higher power densities, more efficient operation (~3.0 hp/lb)
<b>Fuel Cell System</b>	Automotive-derivative compressor, heat exchangers, humidifiers, separator (~0.6 hp/lb)	Integrated heat exchangers, humidifiers, separator into fuel cell; lightweight, more efficient compressor (~1.1 hp/lb)	Humidification, separation, extensive cooling not required (~1.6 hp/lb)
<b>Electric Motor</b>	Automotive-derivative permanent magnet electric motor (~0.7 hp/lb)	Electric motor with advanced cooling and more efficient design (~1.5 hp/lb)	Superconducting electric motor with very efficient and lightweight design (~5.0 hp/lb)
<b>Power Electronics</b>	Automotive-derivative power management and distribution (~0.5 hp/lb)	Higher temperature materials (SiC) and components; advanced cooling; more efficient design (~0.6 hp/lb)	Superconducting electronics for a very efficient and lightweight design (~0.9 hp/lb)
<b>H<sub>2</sub> Storage</b>	Mid-pressure (5000 psi) compressed gas; liquid storage for long-duration missions	Improved high pressure composite tanks; lightweight metal hydrides; lightweight, low-temperature chemical reformation	Liquid system design with low boiloff, high safety; or fuel cell able to use common liquid fuels directly
<b>Batteries</b>	Currently available Li-Ion batteries	Advanced Li-Ion or similar chemistry batteries with higher power density	New battery chemistry with longer life and higher energy density

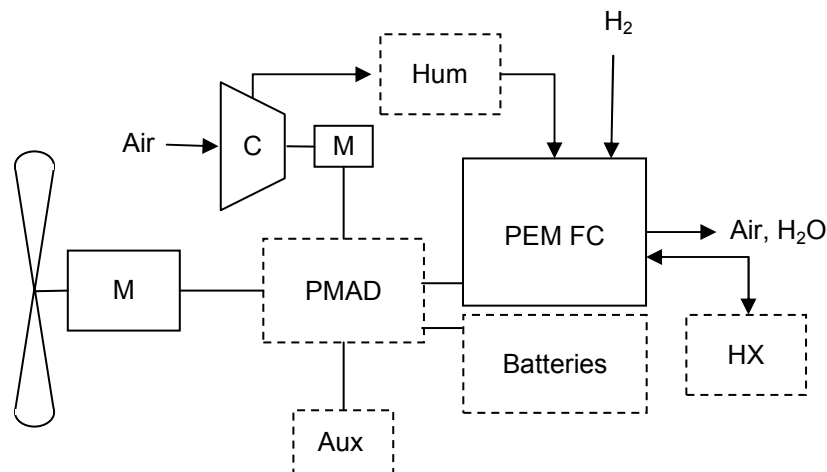


Figure 1.—Fuel cell propulsion system diagram

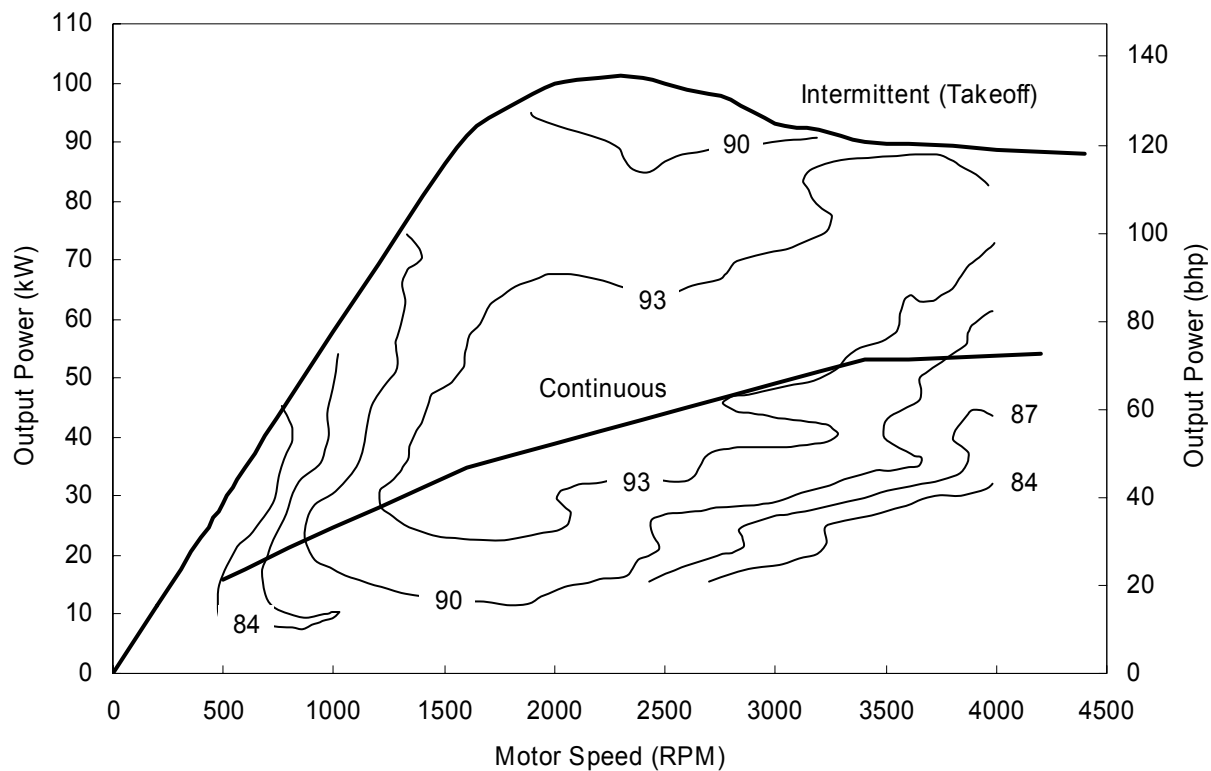


Figure 2.—Unscaled propeller drive motor performance map with efficiency ratings (percent)

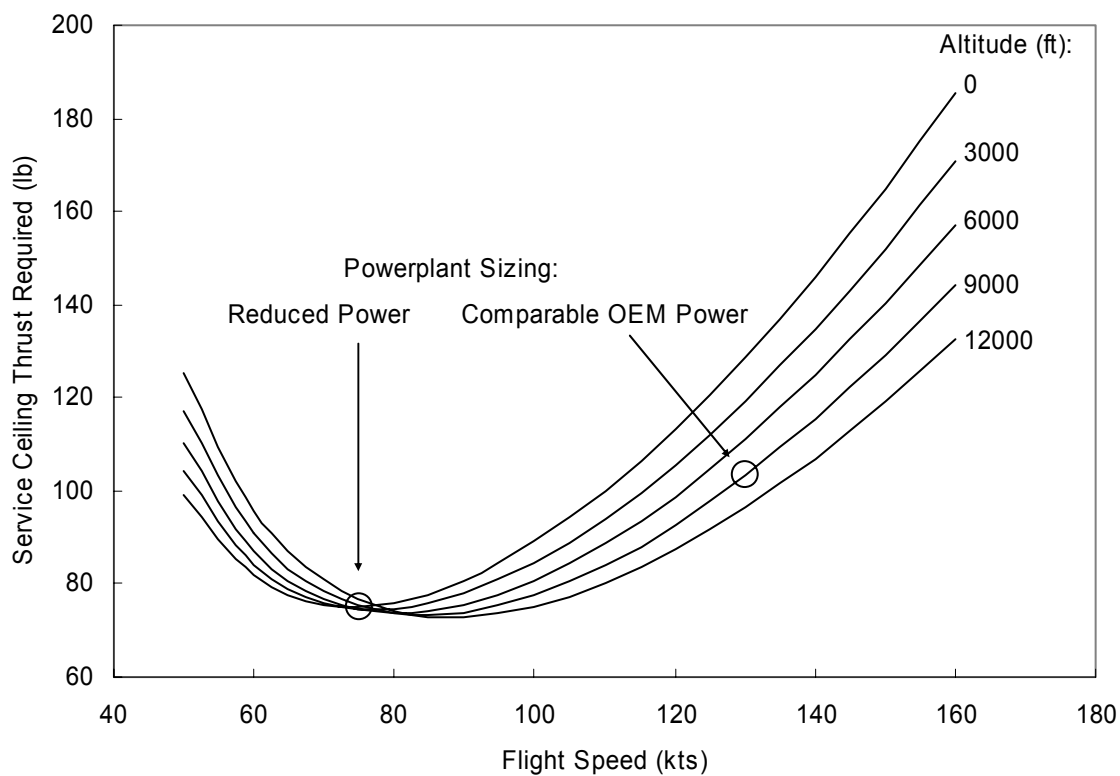


Figure 3.—Thrust power curves used for powerplant sizing

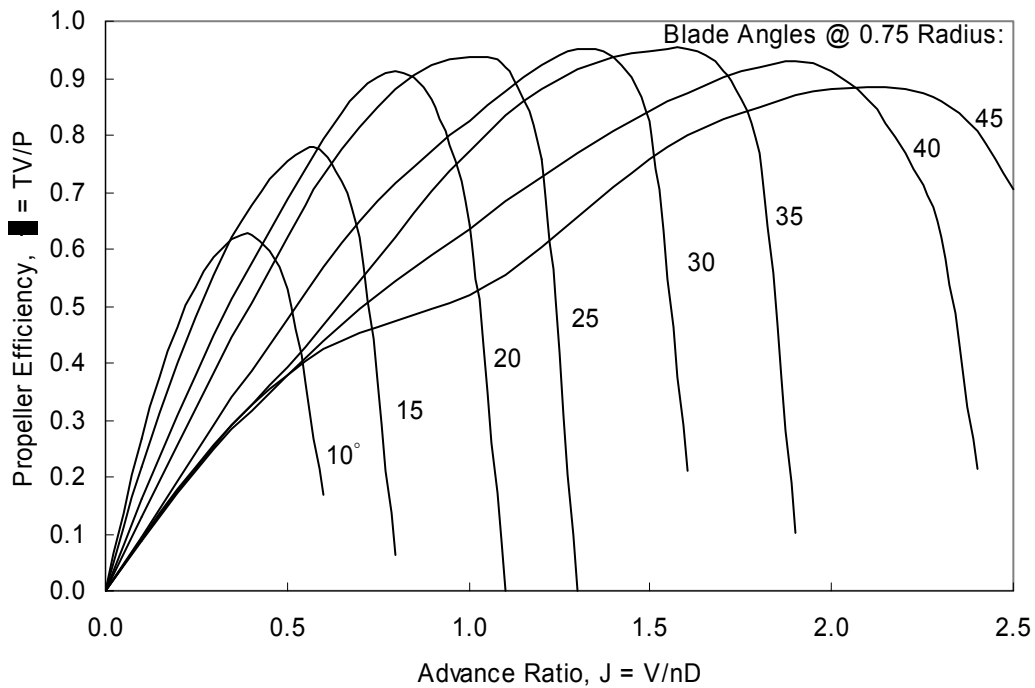


Figure 4.—Propeller performance efficiency chart

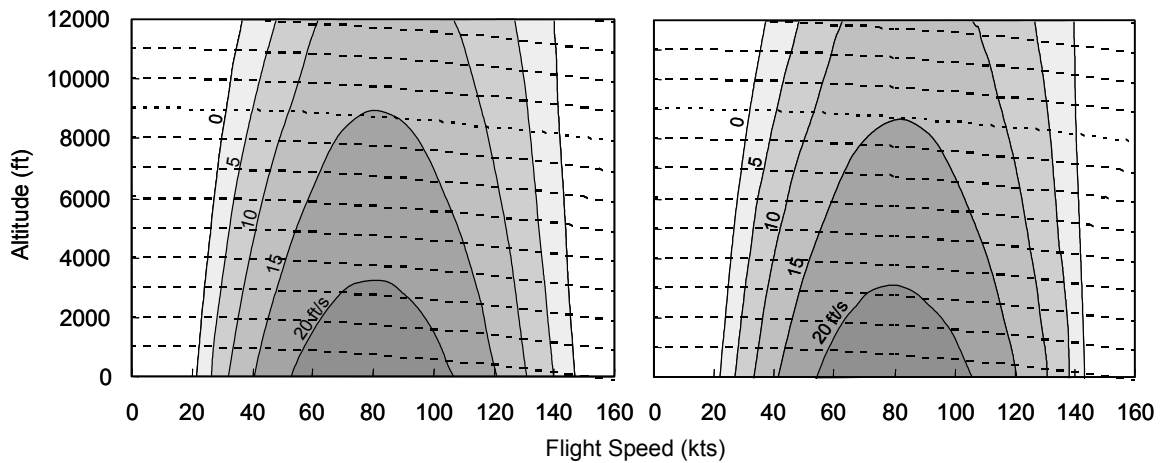


Figure 5.—Takeoff-rated (left) and continuous (right) excess specific power diagrams, 81 bhp Rotax 912A

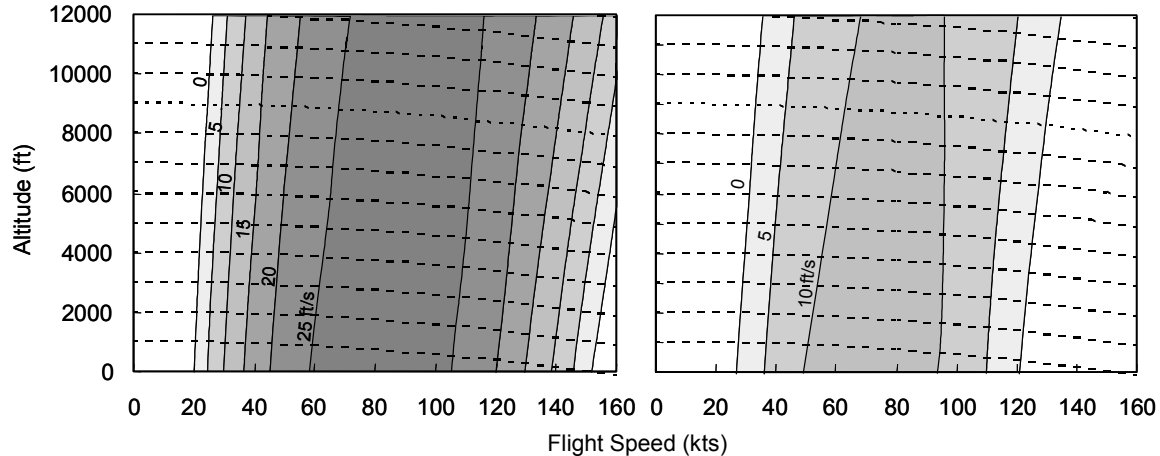


Figure 6.—Takeoff rated (left) and continuous (right) excess specific power diagrams, 81 bhp electric system

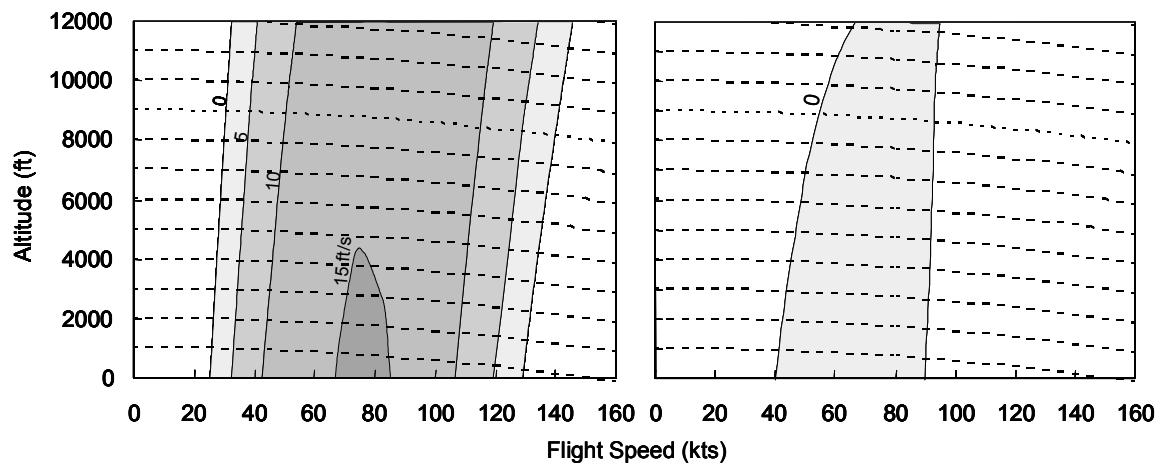


Figure 7.—Takeoff rated (left) and continuous (right) excess specific power diagrams, 49 bhp electric system

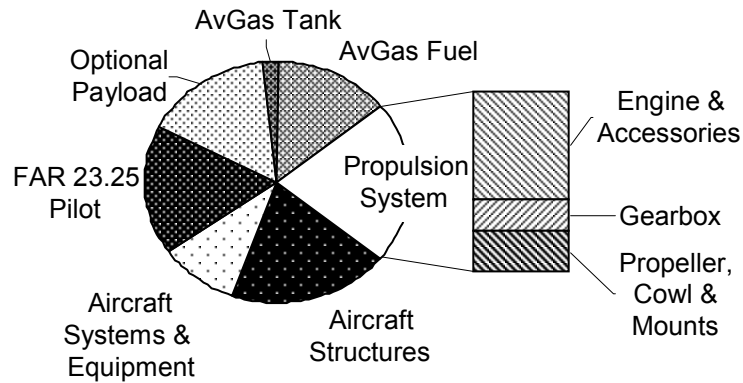


Figure 8.—Takeoff gross weight breakdown: 81 bhp reciprocating engine system with aviation gasoline

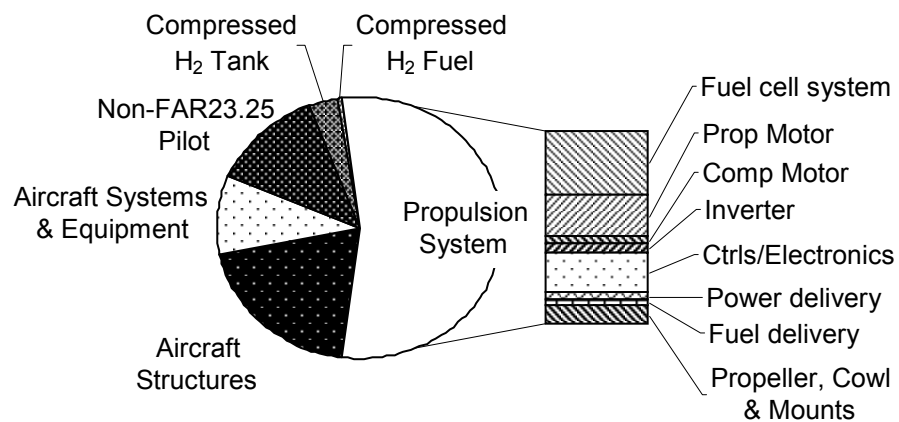


Figure 9.—Takeoff gross weight breakdown:  
81 bhp off-the-shelf technology fuel cell system with compressed H<sub>2</sub>

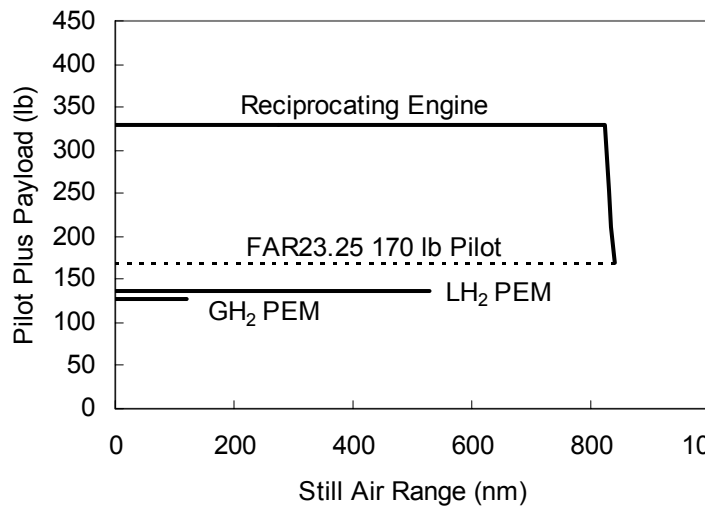


Figure 10.—(Left): 81 bhp PEM and reciprocating systems

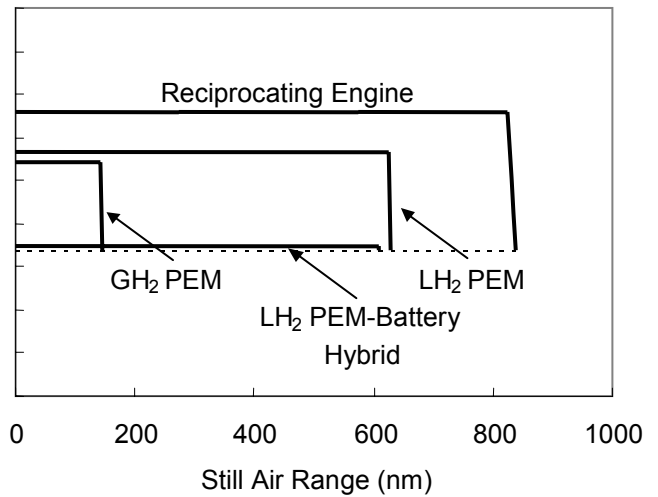


Figure 11.—(Right): 49 bhp PEM, 49 bhp PEM-Battery hybrid, and 81 bhp reciprocating systems

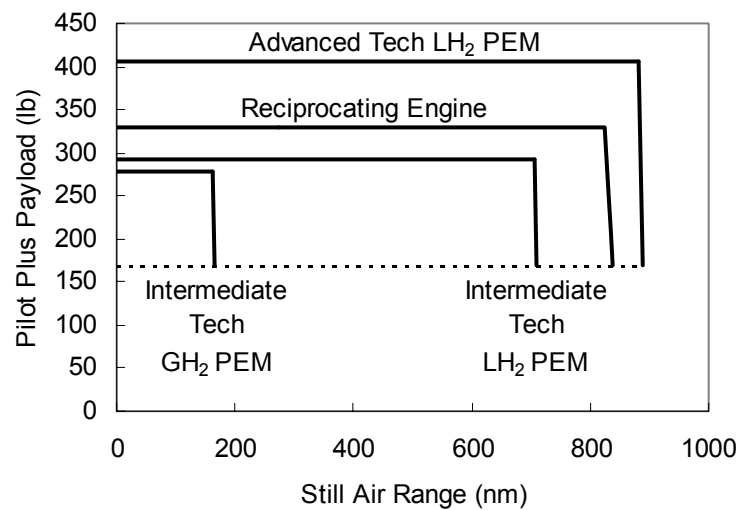


Figure 12.—Intermediate and advanced technology 81 bhp system projections



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